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Review Article

CH_4 and N_2O emissions and their potential control by rice biomass biochar: The case of continuously flooded paddy fields in Indonesia - A review

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Abstract

Methane (CH_4) and nitrous oxide (N_2O) are the two most important greenhouse gases (GHG) from flooded paddy fields in Indonesia. This review aims to characterise CH_4 and N_2O emissions from flooded paddy fields by published data analysis and to examine the potential of biochar from rice straw (RSB) and rice husk (RHB) to mitigate the emissions in Indonesia. A comparison of various box-plot datasets of CH_4 emissions showed that the different types of flooded paddy field soil cause varying amounts of CH_4 emissions from various regions in Indonesia. Sequentially, CH_4 emissions of flooded paddy fields from highest to lowest are Alluvial of Kalimantan and Sulawesi, Andisols of Java, Ultisols of Sumatra, Alfisols of Java and Bali and Inceptisols of Java and Bali, with a mean of 1062, 505, 446, 135 and 64 kg ha^{-1} season^{-1}, respectively. The organic amendments application combined with chemical fertilisers is the principal driver of anthropogenic CH_4 emissions from paddy fields. However, N chemical fertiliser application contributes only about 0.37% of the N_2O flux, 0.69 kg ha^{-1} season^{-1}. The produced biochar number was insufficient effectively to reduce CH_4 and N_2O emissions, at least 20 tonnes ha^{-1} year^{-1}, in addition to the pyrolysis process to produce biochar, releasing CH_4 emissions. Yet, with its recalcitrant

properties and continuous application, RSB and RHB potentially reduce CH_4 and N_2O emissions from paddy fields.

Keywords

paddy field, emissions, soil types, organic amendment, fertiliser, biochar of rice by-product, Indonesia

Introduction

CH_4 and N_2O emissions from flooded paddy fields in the last two decades have continued to increase (Hussain et al. 2014, Susilawati and Setyanto 2018). The flooded paddy field's GHG emissions are under concern in Indonesia as the 3rd rice producer in the world after China and India (FAO 2017). The area of the flooded paddy field is 7.46 million ha and the harvesting area is 10.66 million ha (BP-Statistik 2022). Flooded paddy fields are one of the primary sources of global anthropogenic CH_4 emissions (Feng et al. 2012, Chunmei et al. 2018, Gupta et al. 2021, Tirtalistyani and Murtiningrum 2022). Likewise, the application of N fertiliser is one of the drivers of N_2O emissions and about 70% of N_2O flux is the product of microbial activity in nitrification and denitrification within paddy fields (Braker and Conrad 2011, Butterbach-bahl et al. 2013, Wang et al. 2017, Gupta et al. 2021). Indonesia ranks 3rd in terms of N fertiliser usage in Asia (FAO 2017).

Continuously flooded paddy fields are the preferred method in rice cultivation by almost all farmers in Indonesia (Slamet et al. 2013, Rahmadani et al. 2020). The utilisation of this method simplifies the cultivation and controls weed problems and some rice varieties produce better yields in continuous flooding (Song et al. 2016, Rahmadani et al. 2020, Tirtalistyani and Murtiningrum 2022). For instance, the study of Rachmawati and Retnaningrum (2013) showed that rice cultivation in continuously flooded paddy fields significantly increased plant height, number of tillers, plant biomass and crown root ratio. The emission of CH_4 and N_2O from flooded paddy fields deserves attention because the global warming potential (GWP) of CH_4 was 28 - 36 times the GWP of CO_2, while the GWP of N_2O was 265 - 298 times the GWP of CO_2 (Signor et al. 2013, Han et al. 2016, Vallero 2019).

Several factors in the soil positively correlated with CH_4 formation in flooded paddy fields, including plant biomass, organic C content, dissolved organic C, available N and soil sulphate (Wang et al. 2017). The CH_4 flux from the paddy field, which periodically experiences saturation ranges from 100 – 300 nmol CH_4 g $soil^{-1}$ h^{-1} (Chan and Parkin 2001) and the CH_4 emissions are the end product of the biodegradation process of organic matter or a bio-product of methanogenic activity in anaerobic conditions (Lo et al. 2016). CH_4 emission is formed by anoxic bacteria initiated by incorporating organic matter into paddy soil. The decomposition of organic matter occurs under anaerobic conditions or very limited O_2 and SO_4^{2-}, then the redox potential drops to <150 mV, as well as redox decrease caused by the use of electron acceptors for respiration by microorganisms (Gupta et al. 2021).

The emission of CH_4 was due to management practices, such as organic amendments and water regimes in paddy fields (Yan et al. 2005, Fazli et al. 2016). The application of organic matter like rice straw to paddy fields as much as 6 – 9 tonnes ha^{-1} will increase CH_4 emissions by 1.8 to 3.5 times (Neue et al. 1996) and other factors influencing CH_4 emission are fertilisation and rice variety (Win et al. 2021).

The formation of anthropogenic N_2O in paddy soil is mainly caused by synthetic N fertiliser and organic matter like stirring straw. The N fertiliser-induced N_2O emission factor (FIE) was 1.08% and crop residues-induced N_2O emission factor (RIE) was 0.64% and 0.27% for retained 2.25 - 4.5 tonnes ha^{-1} for each season in China paddy field (Zou et al. 2005). N_2O is a product of microbial activity in transforming nitrogen, namely nitrifier microbes. Nitrosomonas and nitrobacter share with denitrifiers in paddy soil will produce 70% of N_2O emissions (Gupta et al. 2021). Therefore, the formation of N_2O emissions in paddy fields occurs from denitrification under anaerobic and/or nitrification under aerobic conditions (Williams et al. 1992, Wang et al. 2017).

Rice plants acted more as a dampener for N_2O flux, which continued to increase with the addition of N fertiliser to the paddy fields (Kim et al. 2021). Rice is not a source of N_2O emissions, yet their roots play an essential role in N_2O flux, in which they release O_2 into the atmosphere to change the redox status and promote the formation of NO_3- with nitrification, then NO_3- which diffuses into the anaerobic zone will be denitrified to N_2O by the denitrifier (Zhang et al. 2017). Other factors which generally positively correlate with N_2O emission are soil moisture, C content, low C/N of organic matter and other soil properties, such as the availability of electron acceptors, i.e. Fe^{3+}, NO_3- and sulphate (Butterbach-bahl et al. 2013, Wang et al. 2017).

In recent times, one of the ingredients promoted as an alternative technology for controlling CH_4 and N_2O emissions from paddy fields is the use of biochar with the primary feedstock rice biomass (Wang et al. 2011, Song et al. 2016, Yang et al. 2019). Rice biomass is considered to have great potential as by-products, namely rice straw (RS) and rice husk (RH). When converted to biochar by pyrolysis, the combustion of rice organic waste with low oxygen can produce rice straw biochar (RSB) and rice husk biochar (RHB) between 30 – 75% dry weight of RS and RH and the higher pyrolysis temperature results in less biochar; conversely, when the pyrolysis temperature is lower, more biochar is produced (Wu et al. 2012, Claoston et al. 2014, Li et al. 2018).

The potentials of RSB and RHB use in controlling CH_4 and N_2O emissions from paddy fields are continuously studied. Most of the studies are in Asian countries with large areas of paddy fields, such as China, India, Japan, Indonesia and other countries. However, the question is whether a sufficient amount of RSB and RHB from paddy fields themselves are available to control CH_4 and N_2O emissions effectively and whether their utilisation can resolve the problem of GHG emissions from paddy fields if the use of biochar is to be a national policy in a country with a large paddy field such as Indonesia.

This review article intends to characterise CH_4 and N_2O emissions from flooded paddy fields by published data analysis and to examine the potential of biochar from rice straw (RSB) and rice husk (RHB) to mitigate the emissions in Indonesia.

Methodology

Paddy field and harvesting areas

Indonesia is a tropical archipelago country that stretches at 6^o 08' North and 11^o 15' South and from 94^o 45' to 141^o 05' East longitude, covering an area of approximately 8.3 million km^2 with a land area of about 1.92 million km^2 and coastline along 95,181 km (MoEF 2022). Data on paddy field areas, harvesting areas and rice production from the main rice-producing islands in Indonesia compiled in this article refer to the Indonesian statistical book report (BP-Statistik 2022).

Compilation of published CH_4 and N_2O emission data from flooded paddy fields in various regions in Indonesia

The data processed in this article were published data consisting of datasets from various regions in Indonesia as a result of 67 observation points for CH_4 emission and 13 observation points for N_2O emission from flooded paddy fields. The compiled CH_4 and N_2O emission data in a matrix is complemented by the description of cultivation technologies applied on flooded paddy fields, such as observation location, soil type of the paddy field, planted rice variety, type and volume of the organic amendment and chemical fertilisers. The data sources were articles published in peer-reviewed reputable journals in Indonesia and internationally. References for discussion were also from various research articles and reviews in journals claimed by Scimago, such as those published through the Elsevier Science Direct website (https://www.sciencedirect.com/), the Web of Science (apps.webofknowledge.com), Google Scholar (https://scholar.google.com/) and other reputable global-indexed journals, as well as supported by data on progress reports and agricultural development plans in Indonesia which are available on the internet, books and other reliable sources of information.

Analysis of the characterisation of CH_4 emission from the paddy field in Indonesia

Firstly, CH_4 emission data compiled from various references were grouped with Microsoft Excel into several groups of factors that predicted influencing CH_4 emissions from flooded paddy fields. After grouping, the dispersion of the CH_4 emission dataset for each group factor was analysed by the Box and Whisker plot (box plot) in Microsoft Excel. The box plot shows the central tendency of the data distribution, equipped with information on the median (Q2), upper quartile (Q3) and lower quartile (Q1) and the box length (IQR) is Q3-Q1 which is a reflection of the dispersion of the dataset. Q3 and Q1 are the medians for 50% of the data above and below Q2, respectively, with the whiskers as the limits for the highest and smallest data values. Other data information are outlier values and extreme values (Fig. 1). In box-plot comparisons between each dataset, the median line (Q2) was used as a clue for differences between datasets. If the median line is outside the box plot of the other dataset, the two datasets are different (https://www.khanacademy.org/math/statistics-probability/summarizing-quantitative-data/box-whisker-plots/a/box-plot-review); (https://asq.org/quality-resources/box-whisker-plot). Apart from that, an F-test and T-test were carried out to determine the difference in the mean of emissions from paddy fields as an influence of various factors.

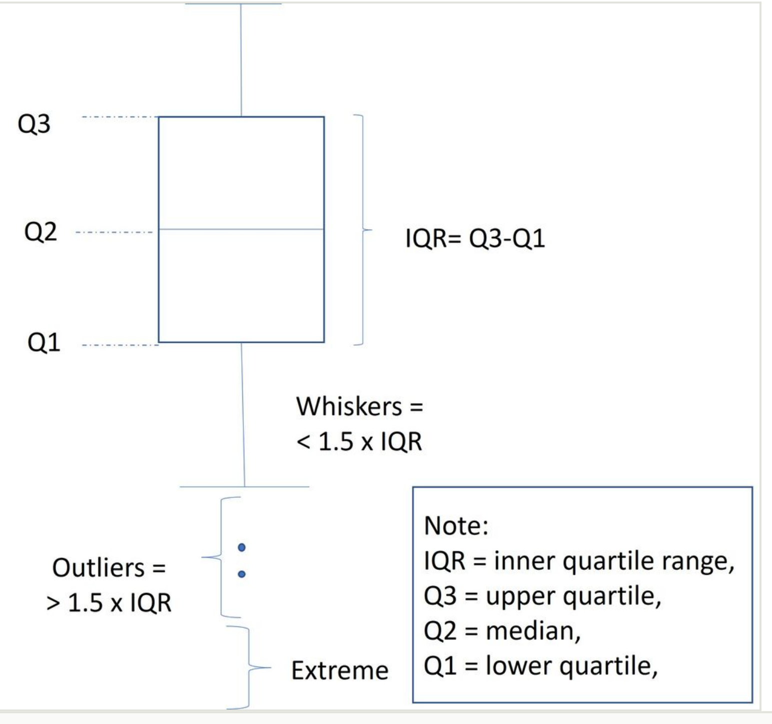

Figure 1.

The display of the box and whiskers plot depicting the dispersion of a dataset.

Analysis N fertiliser-induced N_2O emission (FIE)

An analysis based on the measured N_2O emissions was carried out to determine the N fertiliser-induced N_2O emission factor (FIE). As suggested by Akiyama et al. (2005), Chen et al. (2015) and Weller et al. (2016), the formula to calculate the FIE (%) was N_2O emission from paddy field with N fertilisation (EdN) (kg ha^{-1}) reduced by N_2O emission from paddy field without N fertilisation (EdnoN) (kg ha^{-1}) and divided by N inputs (kg ha^{-1}). The formula is as follows:

FIE = 100(EdN – EdnoN) / N input

The potential of rice straw biochar (RSB) and rice husk biochar (RHB) to reduce CH_4 and N_2O emissions and estimating rice straw (RS), rice husk (RH), RSB and RHB production from paddy fields in Indonesia

The RSB and RHB potential to reduce CH_4 and N_2O emissions from flooded paddy fields is by the literature study. The total production of RS was estimated, based on the rice grain production. Purwandaru (2013) reported that, for every 1 kg of rice grain production, the rice plant produced 1 kg of dry-weight straw. Van et al. (2014) found 1.5 kg of dry-weight straw for every 1 kg of rice grain production. Likewise, Hay (1995) and Matías et al. (2019) found the weight of the straw-to-rice grain ratio was 1.25.

Estimating the amount of RH yielded from the paddy field was also based on previous research (Hay 1995, Anshar et al. 2013,Matías et al. 2019). RH was about 19 – 20% of the weight of the rice grain yield and to estimate the RH production, based on the weight of the rice grain yield, we used the highest presentation value (20%). The rice grain production of Indonesia used the data reported by BP-Statistik (2022). The formula to calculate the RS (tonne year^{-1}) and RH (tonne year^{-1}) production from a paddy field in Indonesia was:

$RS = 1.25P$ and $RH = 0.2P$

where P is the rice grain production of the paddy field in Indonesia (tonne year^{-1}).

Meanwhile, RSB and RHB production from RS and RH pyrolysis was estimated by compiling research data. The data are displayed in graphical form (Fig. 2), showing the relationship between RSB and RHB with RS and RH processed by various pyrolysis temperatures. The estimation of RSB and RHB production was by the power trend-line of graphic A for RSB and B for RHB (Fig. 2).

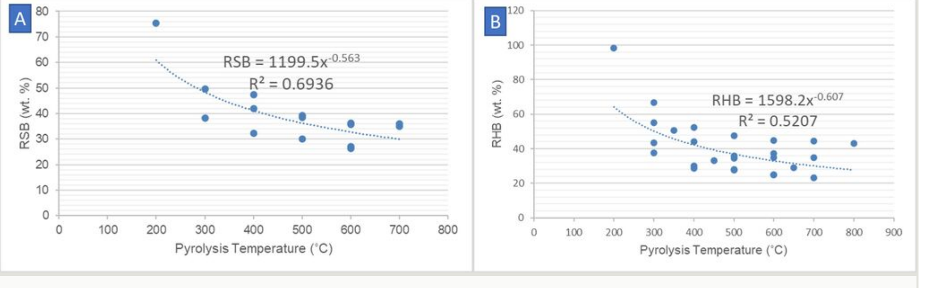

Figure 2.

The percentage of RS to be RSB (A) and RH to be RHB (B) by pyrolysis with various temperatures.

Source: Wu et al. (2012), Claoston et al. 2014, Jun et al. (2015), Yakout (2017), Zhang et al. (2017), Jia et al. (2018), Nwajiaku et al. (2018), Li et al. (2018), Gupta et al. (2019), Zheng et al. (2019), Singh et al. (2020), Laila et al. (2021)

The yield of RSB (wt %) from RS and RHB (wt %) from RH was calculated by the formula:

$RSB = 1199.5x^{-0.563}$ and $RHB = 1598.2x^{-0.607}$

In this case, the x value is the pyrolysis temperature, namely 300 to 500˚C (400˚C as the median) expressed as the pyrolysis temperature providing the better characteristics for RSB and RHB (Wu et al. 2012, Yakout 2017, Southavong et al. 2018, Li et al. 2018, Jia et al. 2018, Singh et al. 2020).

Results and Discussion

Paddy fields and rice harvested area in Indonesia

In 2020, the total area of paddy fields in Indonesia was 7.46 million ha and, by more than one cropping season in a year, the harvested areas reached 10.66 million ha. The three largest paddy fields and harvested areas in Indonesia are in Java Island with 3.47 million ha and 5.4 million ha, respectively, followed by Sumatra with 1.75 million ha paddy fields and 2.3 million ha harvested area and Sulawesi, 973.3 thousand ha paddy field and 1.5 million ha harvested area (Fig. 3) BP-Statistik (2022). However, the highest productivity of paddy fields was in Bali, at 5.89 tonnes ha^{-1}, followed by Java at 5.67 tonnes ha^{-1}.

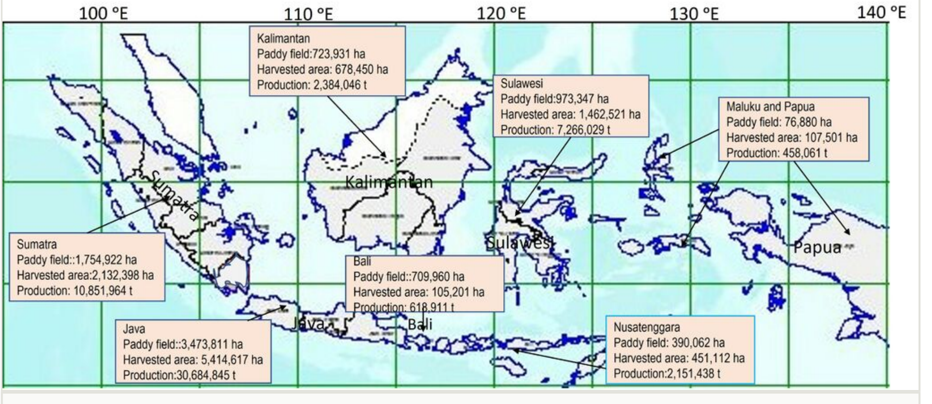

Figure 3.

Paddy fields, rice harvested area and rice production in each main island in Indonesia (BP-Statistik 2022).

The compiled data of CH_4 and N_2O emissions from continuously flooded paddy fields in Indonesia

Data of CH_4 and N_2O emissions per season observed from flooded paddy fields in Indonesia compiled from various references are presented in Table 1.

Table 1.

The compilation of measured available data of CH_4 and N_2O emissions from paddy fields with continuously flooded cultivation systems treated by organic amendment, chemical fertiliser and different rice varieties on different soil types in some islands in Indonesia.

Note: RS= rice straw, FYM = farmyard manure, GM = green manure, GC = goat compost, U = urea, AS = ammonium sulphate, CF = compound fertiliser, TSP = triple superphosphate, SP36 = superphosphate 36, KCl = potassium chloride, UG = urea granule, UT = urea tablet.

Location	Soil type	Rice variety	Organic amendment		Fertiliser	Chemical fertiliser input (kg ha^{-1})			CH_4	N_2O	Reference
			Type	kg ha^{-1}		N	P_2O_5	K_2O	(kg ha^{-1} season^{-1})		
Sumatra, Lampung,	Ultisols	IR-64	0	0	U, AS, TSP, KCl	113	88	60	402	-	Nugroho et al. (1994)
Sumatra, Lampung,	Ultisols	IR-64	0	0	U, AS, TSP, KCl	115	88	60	324	-	Nugroho et al. (1994)
Sumatra, Lampung,	Ultisols	IR-64	0	0	U, AS, TSP, KCl	105	88	60	314	-	Nugroho et al. (1994)
Sumatra, Lampung,	Ultisols	IR-64	RS	5000	U, AS, TSP, KCl	115	88	60	427	-	Nugroho et al. (1994)
Sumatra, Lampung,	Ultisols	IR-64	GM	5000	U, AS, TSP, KCl	115	88	60	390	-	Nugroho et al. (1994)
Sumatra, Lampung,	Ultisols	IR-64	FYM	5000	U, AS, TSP, KCl	115	88	60	341	-	Nugroho et al. (1994)
Sumatra, Lampung,	Ultisols	Bengawan Solo	0	0	U, AS, TSP, KCl	113	88	60	417	-	Nugroho et al. (1997)
Sumatra, Lampung,	Ultisols	IR-74	0	0	U, AS, TSP, KCl	113	88	60	368	-	Nugroho et al. (1997)
Sumatra, Lampung,	Ultisols	IR-64	0	0	U, AS, TSP, KCl	113	88	60	398	-	Nugroho et al. (1997)
Sumatra, Lampung,	Ultisols	Atomita-4	0	0	U, AS, TSP, KCl	113	88	60	326	-	Nugroho et al. (1997)
Sumatra, Lampung,	Ultisols	Cisanggarung	0	0	U, AS, TSP, KCl	113	88	60	365	-	Nugroho et al. (1994)
Sumatra, Lampung,	Ultisols	Way seputih	0	0	U, AS, TSP, KCl	113	88	60	327	-	Nugroho et al. (1997)
Sumatra, Lampung,	Ultisols	Kapuas	0	0	U, AS, TSP, KCl	113	88	60	378	-	Nugroho et al. (1997)
Sumatra, Lampung,	Ultisols	Walanai	0	0	U, AS, TSP, KCl	113	88	60	374	-	Nugroho et al. (1997)
Sumatra, Lampung,	Ultisols	Bengawan solo	RS	5000	U, AS, TSP, KCl	113	88	60	513	-	Nugroho et al. (1997)
Sumatra, Lampung,	Ultisols	IR-74	RS	5000	U, AS, TSP, KCl	113	88	60	637	-	Nugroho et al. (1997)

Location	Soil type	Rice variety	Organic amendment		Fertiliser	Chemical fertiliser input (kg ha^{-1})			CH_4	N_2O	Reference
			Type	kg ha^{-1}		N	P_2O_5	K_2O	(kg ha^{-1} $season^{-1}$)		
Sumatra, Lampung,	Ultisols	IR-64	RS	5000	U, AS, TSP, KCl	113	88	60	536	-	Nugroho et al. (1994)
Sumatra, Lampung,	Ultisols	Atomita-4	RS	5000	U, AS, TSP, KCl	113	88	60	578	-	Nugroho et al. (1997)
Sumatra, Lampung,	Ultisols	Cisanggarung	RS	5000	U, AS, TSP, KCl	113	88	60	597	-	Nugroho et al. (1997)
Sumatra, Lampung,	Ultisols	Way seputih	RS	5000	U, AS, TSP, KCl	113	88	60	646	-	Nugroho et al. (1997)
Sumatra, Lampung,	Ultisols	Kapuas	RS	5000	U, AS, TSP, KCl	113	88	60	573	-	Nugroho et al. (1997)
Sumatra, Lampung,	Ultisols	Walanai	RS	5000	U, AS, TSP, KCl	113	88	60	588	-	Nugroho et al. (1997)
Bali, Gianyar	Inceptisols	IR-74	0	0	0	0	0	0	32.2	-	Subadiyasa et al. (1997)
Bali, Gianyar	Inceptisols	IR-74	0	0	U, TSP, KCl	115	44	30	31.7	-	Subadiyasa et al. (1997)
Bali, Gianyar	Inceptisols	IR-74	RS	5000	0	0	0	0	38.6	-	Subadiyasa et al. (1997)
Bali, Gianyar	Inceptisols	IR-74	RS	5000	U, TSP, KCl	115	44	30	51.5	-	Subadiyasa et al. (1997)
Bali, Gianyar	Inceptisols	IR-74	0	0	0	0	0	0	32.6	-	Subadiyasa et al. (1997)
Bali, Gianyar	Inceptisols	IR-74	0	0	U, TSP, KCl	115	44	30	33.4	-	Subadiyasa et al. (1997)
Bali, Gianyar	Inceptisols	IR-74	RS	5000	0	0	0	0	52.9	-	Subadiyasa et al. (1997)
Bali, Gianyar	Inceptisols	IR-74	RS	5000	U, TSP, KCl	115	44	30	47.4	-	Subadiyasa et al. (1997)
Bali, Gianyar	Inceptisols	IR-64	0	0	0	0	0	0	32.2	-	Subadiyasa et al. (1997)
Bali, Gianyar	Inceptisols	IR-64	0	0	U, TSP, KCl	115	44	30	25.9	-	Subadiyasa et al. (1997)
Bali, Gianyar	Inceptisols	IR-64	RS	5000	0	0	0	0	46.6	-	Subadiyasa et al. (1997)
Bali, Gianyar	Inceptisols	IR-64	RS	5000	U, TSP, KCl	115	44	30	39.5	-	Subadiyasa et al. (1997)
Bali, Gianyar	Inceptisols	Local	0	0	0	0	0	0	26.5	-	Subadiyasa et al. (1997)
Bali, Gianyar	Inceptisols	Local	0	0	U, TSP, KCl	115	44	30	29.7	-	Subadiyasa et al. (1997)

Location	Soil type	Rice variety	Organic amendment		Fertiliser	Chemical fertiliser input (kg ha^{-1})			CH_4	N_2O	Reference
			Type	kg ha^{-1}		N	P_2O_5	K_2O	(kg ha^{-1} season^{-1})		
Bali, Gianyar	Inceptisols	Local	RS	5000	0	0	0	0	67.6	-	Subadiyasa et al. (1997)
Bali, Gianyar	Inceptisols	Local	RS	5000	U, TSP, KCl	115	44	30	53.5	-	Subadiyasa et al. (1997)
Bali Tabanan	Alfisols	IR-64	0	0	0	0	0	0	45	-	Subadiyasa et al. (1997)
Bali, Tabanan	Alfisols	IR-64	0	0	U, TSP, KCl	115	44	30	41.8	-	Subadiyasa et al. (1997)
Bali, Tabanan	Alfisols	IR-64	RS	5000	0	0	0	0	69.6	-	Subadiyasa et al. (1997)
Bali, Tabanan	Alfisols	IR-64	RS	5000	U, TSP, KCl	115	44	30	105	-	Subadiyasa et al. (1997)
Bali, Tabanan	Alfisols	Local	0	0	0	0	0	0	48.2	-	Subadiyasa et al. (1997)
Bali, Tabanan	Alfisols	Local	0	0	U, TSP, KCl	115	44	30	58	-	Subadiyasa et al. (1997)
Bali, Tabanan	Alfisols	Local	RS	5000	0	0	0	0	68.9	-	Subadiyasa et al. (1997)
Bali, Tabanan	Alfisols	Local	RS	5000	U, TSP, KCl	115	44	30	106.8	-	Subadiyasa et al. (1997)
Java, Jakenan	Inceptisols	Membramo	FYM	5000	U, SP36, KCl	120	60	90	61.1	-	Setyanto et al. (2004)
Java, Jakenan	Inceptisols	Cisadane	FYM	5000	U, SP36, KCl	120	60	90	94. 8	-	Setyanto et al. (2004)
Java, Jakenan	Inceptisols	IR-64	FYM	5000	U, SP36, KCl	120	60	90	37.7	-	Setyanto et al. (2004)
Java, Jakenan	Inceptisols	Way apoburu	FYM	5000	U, SP36, KCl	120	60	90	58.9	-	Setyanto et al. (2004)
South Kalimantan	Alluvial	Local	RS	4000	U, SP36, KCl	100	100	100	1251	8.9	Hadi et al. (2010)
South Kalimantan	Alluvial	Local	RS	4000	U, SP36, KCl	100	100	100	1585	-29.6	Hadi et al. (2010)
South Kalimantan	Alluvial	Hybride	RS	4000	U, SP36, KCl	100	100	100	1318	26.6	Hadi et al. (2010)
South Sulawesi	Alluvial	Cigulis	RS	4000	CF, U, AS, SP-36	158	28	10	519	-0.1	Jumadi et al. (2012)
South Sulawesi	Alluvial	Cigulis	RS	4000	CF, U, AS, SP-36	158	28	10	635	-0.1	Jumadi et al. (2012)
Java, Pati	Inceptisols	Cisadane	FYM	5000	U, TSP, KCl	120	90	90	240	1.9	Pramono et al. (2017)

Location	Soil type	Rice variety	Organic amendment		Fertiliser	Chemical fertiliser input (kg ha^{-1})			CH_4	N_2O	Reference
			Type	kg ha^{-1}		N	P_2O_5	K_2O	(kg ha^{-1} season^{-1})		
Java, Pati	Inceptisols	Ciherang	FYM	5000	U, SP36, KCl	120	90	90	280	-2.5	Pramono et al. (2020)
Java, Karanganyar	Andisols	Mentik	0	0	U, CF, SP36	515	59	15	497	-	Kurniawati et al. (2018)
Java, Karanganyar	Alfisols	Ciherang	FYM	1500	U, CF, SP36	198	192	60	467	-	Kurniawati et al. (2018)
Java, Karanganyar	Andisol	Gloutinous	FYM	3000	0	0	0	0	513	-	Kurniawati et al. (2018)
Java, Karanganyar	Alfisols	Cempo Black	FYM	7500	0	0	0	0	342	-	Kurniawati et al. (2018)
Java, Kendal		Ciherang	RS	2000	U, CF	137	34	34	56.4	-	Arianti et al. (2022)
Java, Kendal		Inpari 20	RS	2000	U, CF	137	34	34	22.3	-	Arianti et al. (2022)
Java, Kendal		Inpari 30	RS	2000	U, CF	137	34	34	40.8	-	Arianti et al. (2022)
Java, Kendal		Ciherang	GC	2000	U, CF	137	34	34	58.9	-	Arianti et al. (2022)
Java, Kendal		Inpari 20	GC	2000	U, CF	137	34	34	36.8	-	Arianti et al. (2022)
Java, Kendal		Inpari 30	GC	2000	U, CF	137	34	34	42	-	Arianti et al. (2022)
Java, Bogor	Latosol	IR-64	0	0	0	0	0	0	-	0.35	Suratno et al. (1998)
Java, Bogo	Latosol	IR-64	0	0	0	0	0	0	-	0.59	Suratno et al. (1998)
Java, Bogo	Latosol	IR-64	0	0	UG, TSP, KCl	86	44	60	-	0.63	Suratno et al. (1998)
Java, Bogo	Latosol	IR-64	0	0	UG, TSP, KCl	86	44	60	-	0.81	Suratno et al. (1998)
Java, Bogo	Latosol	IR-64	0	0	UT, TSP, KCl	86	44	60	-	0.68	Suratno et al. (1998)
Java, Bogo	Latosol	IR-64	0	0	UT, TSP, KCl	86	44	60	-	1.05	Suratno et al. (1998)
Average									288.9	0.71	

As presented in Table 1, CH_4 emission data were observation results from the flooded paddy fields in five main islands, Sumatra, Java, Bali, Kalimantan and Sulawesi, while the N_2O emission data were only from the islands of Java, Kalimantan and Sulawesi. The average CH_4 emission from flooded paddy fields on five islands, as the area of paddy field centres in Indonesia, was 288.9 kg ha^{-1} season^{-1} and the average N_2O emission was 0.71

kg ha^{-1} season^{-1} (Table 1). The data were higher than the emission factor (EF) used by Ariani et al. (2015) to estimate the amount of CH_4 and N_2O emissions from paddy fields in Indonesia, namely CH_4 emissions of 160.9 kg ha^{-1} season^{-1} and N_2O emissions of 0.297 kg ha^{-1} season^{-1}. Meanwhile, using the DeNitrification DeComposition (DNDC) model (Munawaroh et al. 2022) obtained an EF value based on the three observatory sites on Java Island; for the values of CH_4, EF was 281.6 kg ha^{-1} per year and for N_2O, EF was 16.9 kg ha^{-1} per year.

Analysis of several factors influencing CH_4 emission from flooded paddy fields

By consideration that, generally, the cultivation technologies applied by farmers to flooded paddy fields in Indonesia are almost in line with the cultivation technologies used in trials conducted in various regions in Indonesia (Table 1), the grouping of data into several factors considered to affect the amount of CH_4 emissions, as follows:

The soil type of paddy fields

The results of grouping and analysis of dispersion and comparison of datasets using Box and Whisker plots (box plot) show that the soil type of paddy fields was a factor that influenced the flux of CH_4. The display of the comparison test between box plots of the CH_4 emission dataset for each soil type (Fig. 4) shows that the median line of each box plot is beyond the box plot of other datasets, except for the median line in the box plot of CH_4 emissions dataset from Andisols and Ultisols and also Inceptisols and Alfisols are seen be within the same range or not significantly different (Fig. 4). Apart from the higher box plot, as an indication of wider data dispersion, the orange colour dominating the alluvial box plot in Q1 shows that more than 50% of CH_4 emission data from Alluvial paddy fields are below the median value. In contrast to the box plot of the CH_4 emission dataset from Ultisols, Alfisols and Inceptisols soil, a shorter box plot and more data distributed above the median (Q3) (indicated by grey colour) are shown. The comparison test display is also supported by the result of the F-test at $P \leq 0.01$, which shows the same results (Table 2). The effects of various paddy field soils on CH_4 emission values have also been reported by Dubey et al. (2014) and Conrad (2020).

The mean of CH_4 emission from Alluvials was the highest and was significantly different from other soils' CH_4 emissions (Table 2). In contrast, the box plot of the CH_4 emission dataset from others appears smaller. However, the CH_4 emission dataset from Alfisols and Inceptisols are also scattered, as shown by long whiskers and some of the data may be outliers.

High CH_4 emissions per season from flooded paddy fields in Alluvial in South Kalimantan (Hadi et al. 2010) are in line with the research results of Setyanto et al. (2002), which categorised grey-yellowish Alluvial as soil with the highest CH_4 emission capacity. However, high CH_4 emissions from flooded paddy fields in this area are also predicted due to the Barito River water as the irrigation source for inundating paddy fields having experienced heavy pollution. Ho et al. (2020) stated that the more polluted the river water is, the higher CH_4 emissions from the water. The polluted Barito River water is predictably due to having passed through a watershed area of 1,090 km (680 miles) from upstream to downstream (https://www.detailedpedia.com/wiki-Barito_River). In 2013, the Barito River water was heavily polluted by waste from coal mining activities, industry and microplastics waste and measured levels of biological oxygen demand (BOD), chemical oxygen demand (COD) and total suspended solids (TSS) have reached 94.8 tonnes, 121.5 tonnes and 51.34 tonnes per day, respectively (https://www.ekuatorial.com/2013/10/indonesian-sungai-barito-tercemar-melebihi-ambang/).

Table 2.

F-test result at $P \leq 0.01$ of soil factor effect on CH_4 emission of paddy fields in Indonesia.

Soil factor	Sample	CH_4 emission mean (kg ha^{-1} $season^{-1}$)
		kg ha^{-1} $season^{-1}$
Inceptisols	22	64.6 ± 65.7 c
Alfisols	10	135.3 ± 146.7 c
Ultisols	22	446.3 ± 113.1 b
Andisols	3	505.0 ± 8.0 b
Alluvial	5	1061.6 ± 461.5 a
p-value		0.000

Means followed by different letters differed at $P \leq 0.01$.

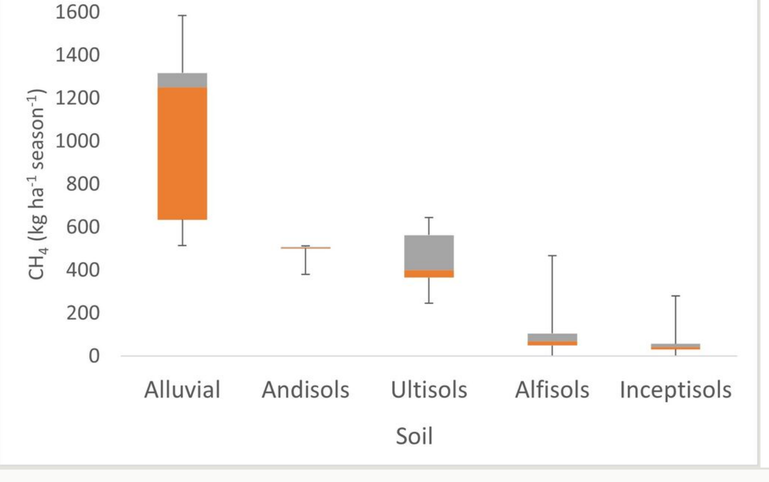

Figure 4.

The comparison of each box plot for the CH_4 emission dataset from flooded paddy fields on various soil types in Indonesia.

Source: Nugroho et al. 1994, Nugroho et al. 1997 , Subadiyasa et al. 1997, Setyanto et al. 2004, Hadi et al. 2010, Jumadi et al. 2012, Pramono et al. 2017, Kurniawati et al. 2018, Pramono et al. 2020, Arianti et al. 2022.

One factor that affects the CH_4 fluxes from the soil is the soil's physicochemical properties (Dubey et al. 2014). The high CH_4 from Andisols (Table 2) is because Andisols have a relatively low Bulk Density (BD) compared to other mineral soils. Soils with lighter BD are rich in porosity, which makes it easier for CH_4 gas to flux (Wanyama et al. 2019). The BD of Andisol soils in Java Island was measured in the range of 0.32 – 0.76 g cc^{-1} in topsoil (Van Ranst et al. 2002, Anindita et al. 2022), while Alfisols' BD measured 1.23 g cc^{-1} (Syamsiyah et al. 2023). The research by Kurniawati et al. (2018) found that the average CH_4 emissions from paddy fields on Andisols with organic amendment FYM 3 tonnes ha^{-1}, namely 513 kg CH_4 ha^{-1} $season^{-1}$, is higher than CH_4 emissions from paddy fields on Alfisols with organic amendment 7.5 tonnes ha^{-1}, i.e. 342 kg CH_4 ha^{-1} $season^{-1}$.

Meanwhile, the higher CH_4 emissions from the flooded paddy field on Ultisols (Table 2) were due to the chemical properties of the Ultisols in Sumatra. Ultisols of Sumatra are rich in iron oxides and manganese (Mn) (Nursyamsi et al. 2000). When reduction due to inundation in paddy fields, electron acceptors such as Fe^{3+} will reduce to Fe^{2+} and Mn^{4+} to Mn^{2+}, followed by a reduction of CO_2 to CH_4 (Nursyamsi et al. 2000, Mohanty et al. 2014). Hence, Fe^{3+} reduction is a principal part of the formation of CH_4 emissions in flooded paddy fields, besides the CH_4 formation occurring through biological processes assisted by the rapidly growing methanogenic bacteria (Wang et al. 1993, Van Bodegom and Scholten 2001). The dataset shows lower CH_4 emissions from paddy fields on Alfisols (135 kg CH_4 ha^{-1} $season^{-1}$) and Inceptisols (64 kg CH_4 ha^{-1} $season^{-1}$) on Java and Bali islands (Table 2), following the research result of Setyanto et al. (2002) which classifies brown-reddish Mediterranean soils (FAO classification) or relevant as Rhodustalfs (Alfisols) (USDA classification) and dark brown Mediterranean or Inceptisols (USDA classification) as soils with low CH_4 emission capacity.

Rice variety

The dataset from observations of CH_4 emissions in various regions of research in Indonesia (Table 1) noted that there were 20 varieties of rice planted in paddy fields in the observation areas with 67 repeated observations. The diversity of CH_4 emissions between regions, the various varieties and the different repetitions make it somewhat difficult to interpret the observed CH_4 emissions as the effect of rice variety.

To facilitate the comparative test with box plots, the grouping of rice varieties then follows the Indonesian government's policy of only sorting rice varieties grown by farmers into three groups, namely superior rice, local rice and hybrid rice (http://cybex.pertanian.go.id/mobile/artikel/69940/VARIETAS-PADI/). Amongst 67 observation points, 56 observations were on paddy fields planted with high-yielding variety, 10 points on paddy fields planted with local variety and one with hybrid variety (Table 1). Due to the CH_4 measurement on the hybrid paddy field being only one, in box plot analysis, it was thus categorised as a part of a high-yielding variety. For that reason, the comparison for the box-plot dataset was only between CH_4 emissions under the influence of high-yielding and local (Fig. 5).

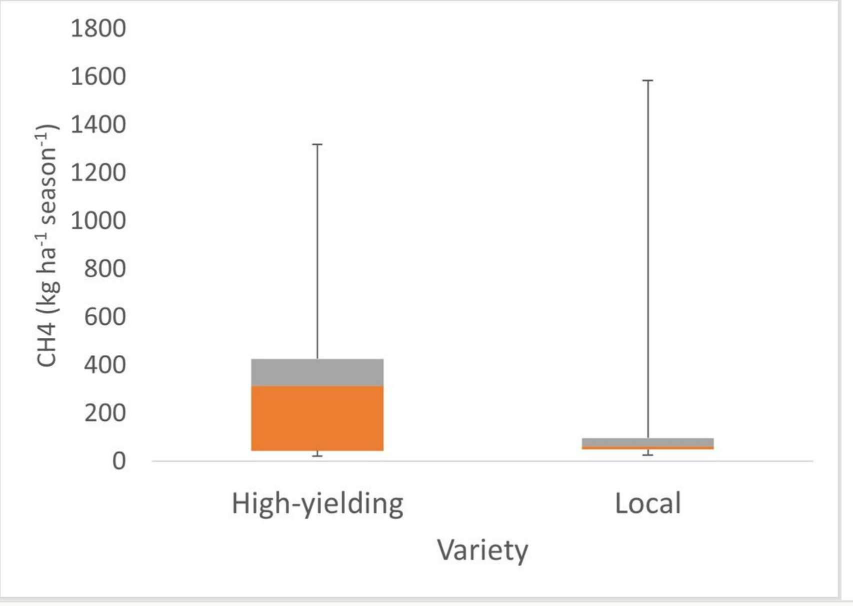

Figure 5.

The comparison of box plots for CH_4 emission dataset from flooded paddy fields planted with superior and local varieties in Indonesia.

Source: Nugroho et al. 1994, Nugroho et al. 1997, Subadiyasa et al. 1997, Setyanto et al. 2004, Hadi et al. 2010, Jumadi et al. 2012, Pramono et al. 2017, Kurniawati et al. 2018, Pramono et al. 2020, Arianti et al. 2022.

A comparison of box plots for datasets of CH_4 emission from the two rice varieties (high-yielding and local) (Fig. 5) shows a different dispersion. Datasets of CH_4 emission from high-yielding variety paddy fields appear with a higher box plot (more dispersed) dominated by orange colour in Q1. It means more data are below the median. Meanwhile, the box plot of the CH_4 emission dataset from local paddy fields shows that the data are not spread out and more data are above the median (Q3) (indicated by grey colour). Yet, the presence of outliers and extreme data in the box plot of the CH_4 emission from the local paddy field (shown by a high whisker) (Fig. 5) makes its mean value slightly higher (Table 3). Due to the median line of this box plot being within the range IQR of the box plot of the high-yielding variety, there is no difference in their mean from the CH_4 dataset of high-yielding varieties. A T-test result shows no significant difference between the mean of CH_4 emission dataset from high-yielding and local paddy fields (Table 3).

Organic amendment and chemical fertiliser

To study the data dispersion and comparative tests of box-plot datasets of CH_4 emissions for the influence of organic amendment and chemical fertiliser factors, one display was carried out (Fig. 6). This was due to the difficulty in testing data dispersion and box-plot dataset comparisons for the effect of various chemical fertilisers with varying patterns of fertiliser doses applied to flooded paddy fields in the observation regions (Table 1).

Table 3.

T-test result of variety effects on CH_4 emission of paddy field in Indonesia.

Variety factor	Sample	CH_4 emission mean (kg ha^{-1} $season^{-1}$)
High yielding	58	278.4 ± 254.5
Local	10	329.7 ± 579.4
p-value		0.640

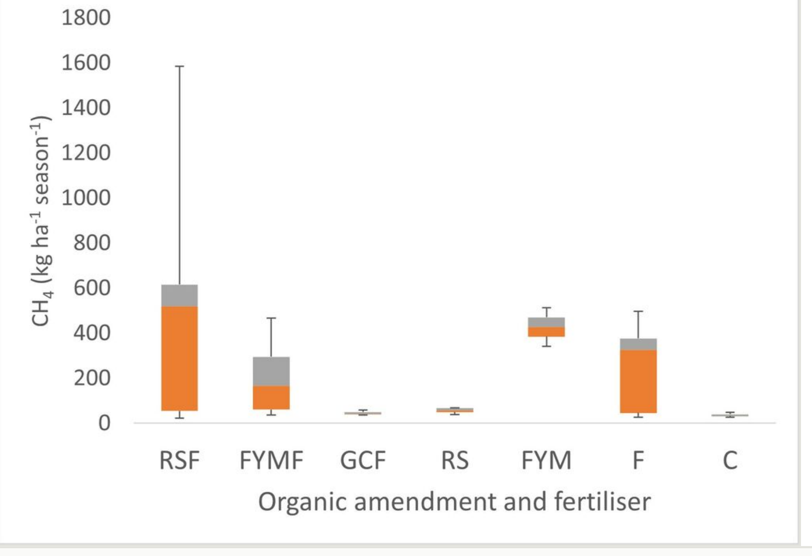

Figure 6.

The comparison of box plots for the CH_4 emission dataset from flooded paddy fields as the effect of organic amendment and chemical fertiliser.

Note: RSF = rice straw+chemical fertilisers, FYMF = farm yard manure+chemical fertilisers, GCF = goat compost+chemical fertilisers, RS = rice straw, FYM = farm yard manure, F = fertilisers and C = control (no organic amendment and chemical fertiliser).

Source: (Nugroho et al. 1994), (Nugroho et al. 1997), (Subadiyasa et al. 1997), (Setyanto et al. 2004), (Hadi et al. 2010), (Jumadi et al. 2012), (Pramono et al. 2017), Kurniawati et al. 2018 (Pramono et al. 2020), (Arianti et al. 2022).

Based on the appearance of the box plot and whiskers (Fig. 6), the dataset of the effect of RSF (interaction of rice straw and chemical fertiliser) is the most dispersed. The box plot of the CH_4 emissions dataset from flooded paddy fields influenced by chemical fertilisers (F) and farm yard manure+fertiliser (FYMF) also shows quite scattered data (Fig. 6). Data of CH_4 emissions for the effect of RSF and F are more spread out in Q1, shown by dominant orange colour in box plot, while, for the effect of FYMF and FYM, the data were slightly more spread out in Q3, shown by the grey colour. However, to compare the mean CH_4 emissions amongst the effects of several factors, just by looking at the box plot appearance, it will show many errors. Therefore, to compare the means, the F-test analysis was carried out. The results are as in Table 4.

Table 4.

F-test result of organic amendment and chemical fertilisers' factor effect on CH_4 emissions of paddy fields in Indonesia.

Organic amendment and chemical fertiliser factor	Sample	CH_4 emission mean (kg ha^{-1} season^{-1})
No organic amendment and chemical fertiliser (C)	7	36.1 ± 7.6 b
Goat compost+chemical fertiliser (GCF)	3	46.0 ± 11.5 b
Rice straw (RS)	7	57.6 ± 12.0 b
Farm yard manure+chemical fertiliser (FYMF)	8	197.6 ± 158.4 ab
Chemical fertiliser (F)	18	261.7 ± 168.9 ab
Farm yard manure (FYM)	2	427.5 ± 120.9 ab
Rice straw+chemical fertiliser (RSF)	23	475.1 ± 439.7 a
p-value		0.054

Means followed by different letters differed at P ≤ 0.10.

The results of the F-test analysis (Table 4) show that the mean of the CH_4 emission dataset from RSF is the highest and is significantly different from the CH_4 emission dataset of RS, GCF and C. The RSF is not significantly different from the CH_4 emission dataset from flooded paddy fields using FYM, F and FYMF. Likewise, the CH_4 emission dataset of FYM, F and FYMF is not significantly different from the dataset of RS, GCF and C. However, the combination of RS and F and FYM and F is the prime driver of CH_4 emissions from flooded paddy fields in Indonesia. The effect of the RS factor alone influencing the CH_4 emission does not look prominent because this CH_4 emission dataset only comes from the research on Alfisols and Inceptisols (Subadiyasa et al. 1997), which are categorised as soils with low CH_4 emission capacity (Setyanto et al. 2002).

Analysis of N fertiliser-induced N_2O emission (FIE)

One of the factors that possibly may be analysed from the available N emission data is the N fertiliser-induced N_2O emission factor (FIE). The data used as material for the FIE analysis are N_2O emissions from flooded paddy fields in West Java only (Suratno et al. 1998). The results of FIE calculations appear in Table 5.

The data from the calculation of FIE in Table 5 show the FIE in tropical flooded paddy fields, especially from Java (West Java) Island, Indonesia, ranging from 0.26% - 0.53% or an average of 0.37% of 0.69 kg ha^{-1} season^{-1}. This FIE was slightly lower than the FIE of flooded paddy fields in China, namely, 0.49% (Chen et al. 2015). Meanwhile, estimates, based on N_2O measurement data in flooded paddy fields in China from the 1950s to 1990s, showed the average FIE was around 0.02% (Zou et al. 2009). On the other hand, the results of data compilation and FIE calculations for N_2O emission report data from paddy fields in China and India found the average FIE of 0.39% and 0.13%, respectively (Akiyama et al. 2005). Overall, the FIE from flooded paddy fields for the three countries, namely China, India and Indonesia (represented by Java Island), was almost the same, of which the N_2O flux from flooded paddy fields derived from N fertiliser applied was 0.13% - 0.39%.

Table 5.

N fertiliser-Induced N_2O Emission (FIE) in flooded paddy field.

*Source: Suratno et al. (1998)

Note: UG = urea granule, UT = urea tablet, TSP = triple superphosphate, KCl = potassium chloride, EFN = N fertiliser-Induced N_2O Emission factor.

Location	Rice variety/ soil type	Amount of organic amendment	Fertiliser type	N Fertiliser inputs	*N_2O emision	Fertiliser-Induced N_2O Emission Factor (FIE)
		kg ha^{-1}		(kg ha^{-1})	(kg ha^{-1} $season^{-1}$)	%
West Java, Bogor	IR-64/Latosol	0	0	0	0.35	-
West Java, Bogor	IR-64/Latosol	0	UG, TSP, KCl	86	0.63	0.33
West Java, Bogor	IR-64/Latosol	0	UT, TSP, KCl	86	0.68	0.38
West Java, Bogor	Cisadane/ Latosol	0	0	0	0.59	-
West Java, Bogor	Cisadane/ Latosol	0	UG, TSP, KCl	86	0.81	0.26
West Java, Bogor	Cisadane/ Latosol	0	UT, TSP, KCl	86	1.05	0.53
Average					0.69	0.37

The potential of RSB and RHB in improving paddy field properties and reducing CH_4 and N_2O emission

The main product of flooded paddy fields is rice grains with by-products of rice straw (RS) and rice husk (RH) that have economic value (Delivand et al. 2011). The by-products of rice planting have been used for a long time to improve the paddy field soil quality by mixing straw into the soil, composting the straw and using rice husk ash as organic fertiliser. The interest in using rice by-products in the form of biochar, such as RSB and RHB, is due to their high C stability.

The benefit of RSB and RHB on the paddy field properties

The high C stability provides some benefits to the ecosystem in paddy fields, namely: a) reducing CO_2 emissions and storing them for a longer time in the soil to mitigate climate change and b) presenting the biochar in the soil to improve soil nutrients and water availability and mitigating agrochemicals and toxins (Lehmann et al. 2006). However, biochar from RS and RH also shows different characteristics. Research results showed biochar from rice straw (RSB) has a high level of alkalinity, available P and N content (Deka et al. 2018), while biochar from rice husk (RHB) has better porosity, ash content, electrical conductivity and increased soil pH (Yakout 2017). One factor influencing the chemical properties of RSB and RHB is the pyrolysis temperature (Claoston et al. 2014). By application of RSB and RHB to the paddy field, 50% C of the organic biomass will be stored as a part of soil organic carbon sequestration by the atmosphere C. Whereas charcoal from burning straw and ordinary husks applied in paddy fields only saved 3% C. Likewise, the straw application in the form of compost only left 10-20% of biomass carbon after 5-10 years (Lehmann et al. 2006). Therefore, the use of organic matter in the form of biochar was the best method to sequester soil organic carbon (SOC) and part of a GWP reduction strategy, especially from flooded paddy fields (Zhang et al. 2015, Song et al. 2016, Yang et al. 2019).

The benefit of RSB and RHB in reducing CH_4 emission from the flooded paddy field

As presented in Table 6, the application of 22.5 tonnes of RSB ha^{-1} reduced CH_4 emissions by 47.30% – 86.43% compared to the CH_4 emissions from paddy fields applied with 6 tonnes of straw ha^{-1} every year. This reduction occurred due to the methanogenic activity in the paddy field being decreased by the biochar application (Dong et al. 2013). These results are also in line with the findings of Han et al. (2016), that the application of RSB as much as 2.5% by dry weight of the soil reduced CH_4 emissions by 39.5%, the methanogenic activity and the increase in the abundance of methanotrophic proteobacteria (Feng et al. 2012, Feng et al. 2013, Liu et al. 2014). Previously, Liu et al. (2011) reported that with the application of RSB of 2.5% weight biochar weight $soil^{-1}$ ($w\ w^{-1}$), CH_4 emissions decreased to 91.2% and Xiao et al. (2018) also found that the use of RSB of 20 tonnes and 40 tonnes ha^{-1} reduced CH_4 emissions from paddy fields by 29.7% and 15.6%, respectively (Table 6).

CH_4 emissions from paddy fields with the application of 5 tonnes of RHB ha^{-1} compared to 5 tonnes of straw ha^{-1}, in combination with the same dose of nitrogen, were lower by 50-60% (Kamala and Bastin 2021). Applying RHB 2% and 4% by dry weight of the soil also reduced CH_4 emissions from paddy fields by 45.2 and 54.9%, respectively compared to the control (Pratiwi and Shinogi 2016). Similar to the result found by Sy et al. (2022), the application of 5 tonnes and 10 tonnes of RHB ha^{-1} significantly reduced CH_4 emission accumulation by 24.2 to 28.0%, respectively compared to without RHB (Table 6). An experiment in Japan found that adding RHB into paddy fields significantly increased soil carbon sequestration without stimulating CH_4 and N_2O emissions (Koyama et al. 2015).

Table 6.

The research results of RSB and RHB reducing CH_4 and N_2O emissions from paddy fields.

Biochar	Application dose	Reduction (%)		Compared to treatment	Reference
		CH_4	N_2O		
RSB	22.5 tonnes ha^{-1}	47 – 86	-	Rice straw 6 tonnes ha^{-1}	Dong et al. (2013)
	2.5% weight biochar weight $soil^{-1}$ (w w^{-1})	39	-	No biochar	Han et al. (2016)
	2.5% (w w^{-1})	91	-	No biochar	Liu et al. (2011)
	20 tonnes ha^{-1}	30	58	No biochar	Yang et al. (2019)
	40 tonnes ha^{-1}	6 - 16	43	No biochar	Yang et al. 2019
	20 tonnes ha^{-1}	30	-	No biochar	Xiao et al. (2018)
	40 tonnes ha^{-1}	16	-	No biochar	Xiao et al. 2018
	40 tonnes ha^{-1} - N	-	59	No biochar	Aamer et al. (2021)
	40 tonnes ha^{-1} + N	-	62	No biochar	Aamer et al. 2021
RHB	5 tonnes ha^{-1}	50 - 60	-	FYM 5 tonnes ha^{-1}	Kamala and Bastin (2021)
	2% (w w^{-1})	45		No biochar	Pratiwi and Shinogi (2016)
	4% (w w^{-1})	55		No biochar	Pratiwi and Shinogi 2016
	5 tonnes ha^{-1}	24	38	No biochar	Sy et al. (2022)
	10 tonnes ha^{-1}	28	56	No biochar	Sy et al. 2022
	50 tonnes ha^{-1}		73	No biochar	Wang et al. (2011)

The benefit of RSB and RHB in reducing N_2O emission from the flooded paddy field

As revealed by Wang et al. (2011), paddy fields are the primary source of anthropogenic N_2O. Biochar utilisation can reduce N_2O emissions from paddy fields by inhibiting nitrification and denitrification processes (Liu et al. 2014), inducing the immobilisation of available N and, thereby stopping N_2O production (Deluca et al. 2006). Applying 20 tonnes and 40 tonnes ha^{-1} of RSB reduced N_2O emissions in the second season by 58.0% and 43.1%, respectively (Yang et al. 2019). Aamer et al. (2021) found that using RSB 40 tonnes ha^{-1}, N_2O emissions from flooded paddy fields with -N was reduced by 59% and with +N reduced by 62%. Meanwhile, Wang et al. (2011) also found that using RHB 50 tonnes ha^{-1} could reduce N_2O emissions by up to 73.1%. Therefore, biochar use promises to reduce the global warming potential (GWP) of paddy field emissions of CH_4, CO_2 and N_2O (Singla and Inubushi 2014, Aamer et al. 2021).

The application of RHB 5% of soil weight (w w^{-1}) significantly reduced cumulative N_2O emissions of 15.2 and 5.8 µg N kg^{-1} when applied as a supplement for NO_3--N fertilising at low and high doses compared to without the addition of RHB (Zhou et al. 2021). These should be a reason for concern since NO_3--N fertiliser use was the main driving factor for increasing N_2O emissions and the increase was 9.7–11.5 times more than the additional N in NH_4^+-N fertilisers (Zhou et al. 2021). However, NH_4^+-N fertiliser was more prominent in increasing N emissions from paddy soil (Wang et al. 2011). Meanwhile, the RHB addition of 26.67 g kg^{-1} (50 kg RHB ha^{-1}) to the soil fertilised by 200 g N kg^{-1} soil reduced cumulative N_2O emissions by up to 73.1% compared to without RHB addition.

Estimation of RS, RH, RSB and RHB production from the paddy fields in Indonesia

Based on the annual rice grain production and the formula to estimate the RS and RH production, as well as the RSB and RHB production (stated in the Methodology), it is estimated that paddy fields of Indonesia can produce RS of 68.31 million tonnes and RH of 15.30 million tonnes per year. Then, by 400˚C pyrolysis, yields of RSB weighing 41.12% of the RS and RHB weighing 42.09% of the RH can be achieved or RSB and RHB 28.09 and 6.44 million tonnes, respectively can be produced (Table 7). These results were obtained if all RS and RH production in Indonesia converted to biochar.

Table 7.

Estimation of RS, RH, RSB and RHB production from the paddy field in Indonesia.

*Source: BP-Statistik (2022)

Indonesian Islands	*Rice grain Production	Rice straw (RS) production	Rice husk (RH) production	RSB	RHB	Total biochar production
	Million tonnes					
Sumatra	11.56	14.45	3.24	5.94	1.36	7.30
Java	30.63	38.29	8.58	15.74	3.61	19.36
Bali	0.53	0.66	0.15	0.27	0.06	0.34
Nusa Tenggara	2.04	2.55	0.57	1.05	0.02	1.07
Kalimantan	2.68	3.35	0.75	1.38	0.32	1.69
Sulawesi	6.85	8.57	1.92	3.52	0.81	4.33
Maluku	0.15	0.19	0.04	0.08	0.02	0.10
Papua	0.19	0.23	0.05	0.10	0.02	0.12
Indonesia	54.65	68.31	15.30	28.09	6.44	34.53

The constraints to convert the RS and RH to RSB and RHB

So far, Indonesian farmers have used RS and RH to improve the soil paddy fields' quality. By-products returned to the paddy field are still undertaken by conventional technologies, such as using straw by stirring it into paddy fields, composting before returning or burning the straw and husks to obtain ash as organic fertiliser. Until now, it is rare to find rice farmers who deliberately use RS and RH as biochar feedstock and then apply them to the paddy fields. In the future, if there is a national agricultural policy to make use of biochar from by-products of rice to reduce the impact of paddy fields on global warming, two obstacles will be encountered as follows:

Rice straw and husk are by-products with economic value

Farmers use RS and RH for additional income. Around 31-39% of them are used as feed or sold to those who need a straw and husk for planting media for ornamental plants and mushroom cultivation. About 7-16% is for industrial raw materials like cleaning tools and bio-energy (Martawidjaya 2003, Purwandaru 2013, Yahya 2017). Thus, only around 60% of RS and RH production is potentially converted to biochar feedstock. If the Ministry of Agriculture invites the farmers to use RSB and RHB to paddy fields to reduce global warming potential (GWP), then the amount of RSB and RHB produced is only around 20.71 million tonnes per year, namely 60% of the total RS and RH production by flooded paddy fields. By dividing them with the paddy field areas in Indonesia, 7.46 million ha (BP-Statistik 2022), only 2.78 tonnes ha^{-1} $year^{-1}$ biochar are available for every 1 ha flooded paddy field. This amount was far below the required RSB and RHB to effectively reduce CH_4 and N_2O from paddy fields, which is 20 to 40 tonnes ha^{-1} respectively (Song et al. 2016, Xiao et al. 2018, Aamer et al. 2021).

Biochar production emits synthesis gas (syngas)

Biochar is considered waste and its production is strictly regulated by the European Directive on Waste (2008/98/EC) (The European Parliament 2008). Despite the beneficial effects of biochar application, its pyrolysis process (temperature 350 - 700˚C) will release by-products, synthesis gas (syngas), with the constituents being CO, H_2, CO_2 and CH_4 (Dunnigan et al. 2016, Glushkov et al. 2021). Using RSB and RHB to flooded paddy fields reduces CH_4 emissions, but its manufacture also releases CH_4 emissions into the atmosphere. CH_4 gas in the biomass pyrolysis process is formed due to the degradation of methoxyl (-O-CH_3) in lignite in biomass (Glushkov et al. 2021). A system pyrolysis model to assume the amount of syngas from biomass pyrolysis like CH_4 gas depends on the pyrolysis temperature (Swagathnath et al. 2018). The results of the modelling pyrolysis system show that, for every 1 kg of RSB produced at a temperature of 400˚C (the temperature used to predict RSB results), it will release ± 50 g of CH_4 emissions. That means if the amount of RSB produced is 16.85 million tonnes (60% of 28.09 million tonnes) (Table 7), then the CH_4 emissions released by the RSB pyrolysis process are 0.84 million tonnes or 5% of the weight of RSB. Likewise, Sparrevik et al. (2015) reported that 15.6 g of CH_4 is emitted per kg RHB production or as much as 0.06 million tonnes of CH_4 in producing 3.86 million tonnes (60% of 6.44 million tonnes) (Table 7) of RHB. It all means that, to yield RSB and RHB, as much as 20.7 million tonnes will release about 0.9 million tonnes of CH_4 emissions. Meanwhile, the amount of CH_4 emissions from paddy fields in Indonesia per year is assumed to be 3.08 million tonnes, from an average CH_4 emission of

288.9 kg ha^{-1} (Table 1) for the paddy harvest area of 10.66 million ha. It is crucial because, before using RSB and RHB in flooded paddy fields, firstly, CH_4 emissions to the atmosphere increase as the contribution of CH_4 released in making biochar. Meanwhile, the percentage of CH_4 emissions from flooded paddy fields reduced by RSB and RHB cannot be predicted with certainty, as the research results vary as in Table 6. The RSB and RHB numbers to reduce CH_4 emissions from flooded paddy fields are also insufficient.

Encouraging factors to use biochar to control emissions from flooded paddy fields

Although the amount of RS and RH from paddy fields is insufficient to meet the needs of biochar in reducing CH_4 and N_2O from the flooded paddy fields themselves, the advantages of biochar including high C stability, resistance to physical aging, chemical oxidation and microbes degradation (Yang et al. 2022) will assist in meeting the need by successive use over several years. Besides that, Nan et al. (2020) found that using biochar in flooded paddy fields successively was better for reducing emissions than a high replication rate. In addition, with the extraordinary nature of biochar that plays a role in maintaining the balance of C in the atmosphere, it is appropriate for farmers not only to rely on rice by-products, but also to look for alternative organic materials as biochar feedstock. Biochar can be produced from various organic materials, such as wood, manure, plant litter, forest products, agricultural valleys, animal manure, urban waste and other organic materials rich in lignocellulose (Downie et al. 2009). Besides, farmers or agricultural policy-makers continue to improve the pyrolysis system towards low or even zero-emission technology for biochar production in Indonesia.

Conclusions

The contribution of paddy fields in Indonesia to CH_4 and N_2O emissions is quite concerning because Indonesian paddy fields are the third largest in the world, after China and India. Dispersion analysis of the CH_4 emission dataset, using the box plot followed by the F-test comparison for the mean, obtained significant differences in CH_4 emission datasets between soil types of flooded paddy fields from various regions in Indonesia. The highest mean of CH_4 emissions with a relatively highly dispersed dataset is CH_4 emissions from flooded paddy fields in the Alluvial soils of Kalimantan and Sulawesi (1062 kg ha^{-1} season^{-1}), followed by CH_4 emissions from the paddy field in Andisols of Java (505 kg ha^{-1} season^{-1}), Ultisols of Sumatra (446 kg ha^{-1} season^{-1}), Alfisols of Java and Bali (135 kg ha^{-1} season^{-1}) and Inceptisols of Java and Bali (64 kg ha^{-1} season^{-1}). The organic amendments of rice straw with chemical fertilisers in paddy fields are the principal driver of CH_4 emissions from flooded paddy fields. The N fertilisers' contribution to N_2O emissions from flooded paddy fields was only about 0.37%. The CH_4 emission can be reduced by RSB and RHB application by their ability to store carbon in the soil and reduce the methanogenic activity of soil microbes, while N_2O emission decreases due to RSB and RHB inhibiting nitrification and denitrification processes. However, the production of RSB and RHB is insufficient to meet the amount required to effectively reduce CH_4 and N_2O

from paddy fields, at least 20 tonnes ha^{-1} per year, while their production by pyrolysis also releases CH_4 gas. Due to their high C stability, resistance to physical aging, chemical oxidation and microbes degradation, with successive use over several years, the RSB and RHB in paddy fields will meet the desired requirements to control CH_4 and N_2O emissions.

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Conflicts of interest

The authors have declared that no competing interests exist.

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